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INVESTIGATION OF THE SUN'S X-RAY RADIATION

(I)

Measurements with the help of GeophysicalRockets

(Issledovaniya rentgenovskogo izlucheniya Solntsa I)

(Ismereniya pri pomoshchi geofizicheskikh raket )

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I. Introduction

In the current, and in the two subsequent communications, expounded are the [results and the method of experiments concerning the study of X-ray radiation of the Sun in the region of the spectrum shorter than  $10 \text{ \AA}$ , carried out during the vertical launchings of geophysocal rockets, and on the 2nd and 3rd spaceships-satellites]. The preliminary results of these measurements have been briefly outlined earlier [1].

The theoretical investigation of the [Sun's short-wave radiation, including the soft X-ray region of the spectrum], was first conducted by I. S. Shklovskiy [2, 3]. Subsequently, similar computations were carried out by Elwert [4], de Jager [5], T. V. Kazachevskaya and G. S. Ivanov-Kholodnyy [6], and lately again by Elwert [7].

The first experimental measurement of solar X-ray radiation have been carried out by H. Friedman and his collaborators with the help of altitude rockets [8 - 13]. Photon counters served as receivers, in which beryllium and aluminum foil windows, together

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with organic films acting as filters, outlined separate portions of the spectrum 0 - 8 Å (Be), 0 - 20 Å (Al), 44 - 60 Å ( maylar) 44 - 100 Å (gliptal')\*)

Measurements completed in a series of works by Friedman stretched over the 11-year cycle of solar activity. Radiation flux in the region 0 - 20 Å resulted subject to significant variations correlated with solar activity. Radiation flux in the region 0 - 8 Å varied within the limits from  $3 \cdot 10^{-6}$  to  $1.5 \cdot 10^{-3}$  ergs. $\text{cm}^{-2}.\text{sec}^{-1}$  in the assumption that the emission spectrum is continuous, and that the energy distribution in that region of the spectrum corresponds to the color temperature  $T \sim 1.5 \rightarrow 2 \cdot 10^6$  °K. The radiation flux in the region 44 - 100 Å was significantly more stable, constituting about 0.1 - 1 erg  $\text{cm}^{-2}.\text{sec}^{-1}$ , and corresponded to a color temperature of the order of  $5 \cdot 10^5$  °K.

Besides, several measurements of radiation flux in the region 0 - 8 Å and 0 - 20 Å were made by Friedman and his collaborators during chromospheric flares. It was established that during flares, the boundary of the spectrum shifts to the shortwave region and radiation flux in the region 0 - 8 Å increases to about  $10^{-2}$  ergs. $\text{cm}^{-2}.\text{sec}^{-1}$  for a class 2+ flare. An assumption was made by Friedman, that owing to the shifting during a flare of the shortwave boundary of radiation, the latter penetrates deeper in the terrestrial atmosphere, and induces a lowering of the boundary of the ionosphere D-layer by about 15 km. This is being revealed in time of sudden ionospheric disturbances.

These results constitute a significant interest for the understanding of physical processes taking place in outer envelopes of the Sun, and of those of Earth's ionosphere formation. The available material naturally still is quite insignificant, and that is why a further systematic accumulation of experimental data with the help of rockets and satellites is desirable.

\*[the last two are transliterated]

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Measurements at vertical launchings of rockets constitute interest, because at rocket's passing through the atmosphere, various zones of Sun's X-ray radiation undergo different absorptions. Thanks to that, as was shown by Friedman, it becomes possible to determine the energy distribution in the X-ray spectrum of the Sun.

Investigations by means of Earth satellites provide the possibility of studying the variations of radiation flux, and of the spectral composition of the emission in time, which is of particular interest.

## 2. Method of Measurements

We selected as the first problem [the measurement of radiation flux near the short-wave edge of the Sun's spectrum — shorter than  $10 \text{ \AA}$ .] This radiation is emitted from the hottest parts of the solar corona. As was shown, it is subject to fast variations, related to dynamics of processes taking place in the solar corona, and it is the object of the deepest penetration into the terrestrial atmosphere.

The measurements described in the present paper, were conducted during two vertical launchings of geophysical rockets. The immediate objective of these measurements consisted in the accumulation of experimental material, and the working out of a method for subsequent measurements by means of satellites.

We used photon counters as receivers, on account of their higher sensitivity in the spectrum region shorter than  $10 \text{ \AA}$ , than that of vacuum photomultipliers.

The pick up block was placed outside the instrument container. The latter separated from the rocket. It was self-orienting by the Sun, and it remained so oriented during the remainder of the ascending portion of rocket's trajectory, as well as during the descending one, through reentering dense layers of the atmosphere (40 km).

In view of indications of the existence at 70 km altitude and above of corpuscular streams in middle geographic latitudes [14], special dispositions were taken by us so as to ensure an adequate shielding, bearing in mind that the registered radiation was the Sun's X-ray radiation.

During the first launching the block of pick ups contained two Sun-oriented counters of the same type. One of them had a magnetic shielding, effective through energies of 15 – 20 keV, the other (check counter) was devoid of magnetic shield. Such counter combination permitted the estimate the number of readings due to brehmstrahlung, created at the input window of the counters by low-energy electrons. In order to estimate the contribution of faster particles, not deviated by the magnetic shield, a check counter provided with a magnetic shield was utilized at the second launching, with the difference though, that it was turned away from the direction of the Sun by an angle of  $15^\circ$ , thus registering only the radiation of non-solar origin.

The disposition of counters in pickup blocks is shown in Fig.1, where the scheme with the Sun-diverted check counter is represented at the left side, and that with the check counter devoid of magnetic shield from electrons – at the right side.

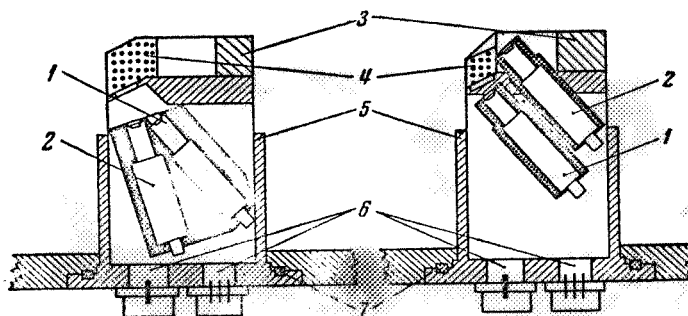


Fig. 1. Schematic cut-away view of the pickup block  
(two variants)

1 — operating counters ; 2 — check counters ; 3 — magnet ;  
4 — pole of the magnet ; 5 — frame ; 6 — ?  
7 — vacuum compression.

The field intensity in the magnet gap was of about  $10^3$  oe. In all cases the counters were covered on the side by a layer of lead about 2 mm thick.

Standard self-quenched counters SBT-9 with a mica end-window were used; they were 4 mm in diameter and  $1.6 \text{ mg.cm}^{-2}$  thick. In order to suppress the existing low counter sensitivity to solar ultraviolet radiation, the mica was sprayed by an aluminum layer about 2 mm thick.

The transparency of the window and of the gas for X-ray radiation in counter's "dead space", and the magnitude of the useful absorption in the operating volume of the counter, were calculated by us, starting from mass absorption coefficients, brought out by Victoreen [15] to the K-quantum, and extrapolated beyond that limit by the formula. The counter's sensitivity  $\eta(\lambda)$  was computed in pulse/quanta in the assumption, that every quantum absorbed in the working volume of the counter, gives a reading. The validity of admissions utilized in the computation of sensitivity, is corroborated by the results of laboratory measurements of counter sensitivity to continuous radiation of an X-ray tube with a Wolfram anode. The intensity and the spectral composition of wolfram anode's radiation were computed by the formula. The open X-ray tube and the counter were placed in a vacuum, so as to eliminate absorption in the air.

As a result of measurements, it was established that counter sensitivities of the studied lot (50 sp.) differ 2 to 3 times, and correspond to computed values with the same degree of accuracy. Compared were also measurements of the absolute sensitivity of a series of emission lines for several specimens of counters. These were carried out according to the method described in [16], in the Leningrad University, simultaneously with those of the author Lukirskiy. These results are plotted in Fig. 2, where the computed sensitivity curve is also represented. The measurement errors apparently

do not exceed 10%. However, the efficiency of the counters employed during rocket launchings, is known to us only to a precision of the factor 2-3 according to measurements on the wolfram anode radiation.

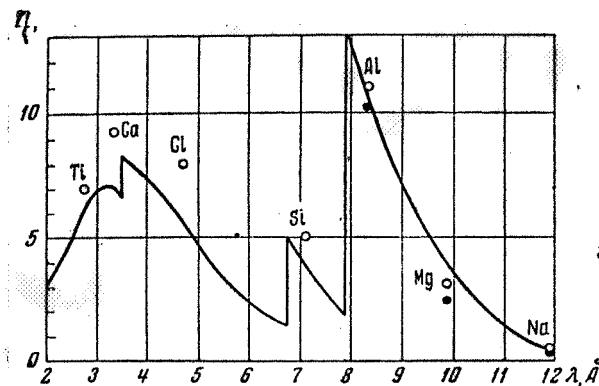


Fig. 2. Counter sensitivity ( $10^{-2}$  pulse  $\cdot$  quant. $^{-1}$ ) as a function of the wavelength.

Clear and black circles represent the results of measurements for two specimens of counters. The computed sensitivity is plotted by the solid line.

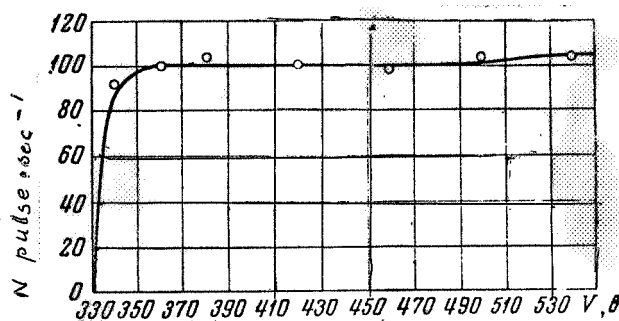


Fig. 3. Counting rate  $N$  as a function of voltage  $V$  in the counter's anode (counting rate versus voltage ch.)

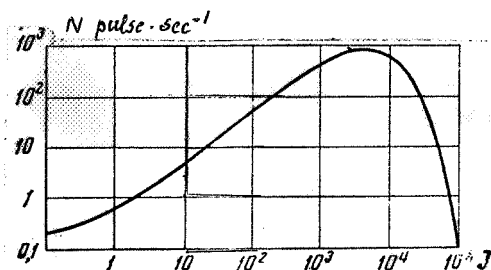


Fig. 4. Counting rate  $N$  as a function of irradiation intensity  $J$ , (in relative units)

The counting rate and calibration characteristics of the counters used, are represented in Fig. 3 and 4. As follows from Fig. 4, the correction for counters' "dead time" exerts little effect upon the counting rate to values through  $400 \text{ pulse} \cdot \text{sec}^{-1}$ .

From counters, pulses entered two scaling circuits consisting of eight binary cells each. The state of the last five cells of each of the scaling circuits was telemetered to Earth, and the counting rate was computed according to these data.

### 3. Results of Measurements

Rocket launchings with the above-described equipment were conducted on 21 July 1959, morning and evening. The solar activity was considerable on that day, with the main center of activity situated at the western edge of the Sun, and a second — weaker one — near its northeastern edge. The relationship of intensities of the green and red coronal lines

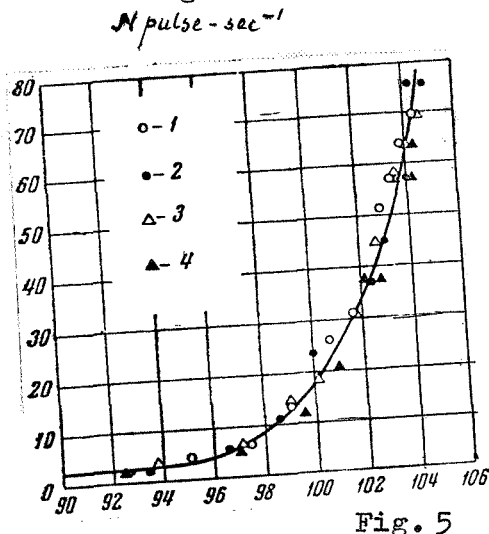


Fig. 5

Counting rate as a function of the altitude of container's lift.

21 July morning launching  
Measurements at ascent and descent  
1, 2 — basic counter  
3, 4 — check counter

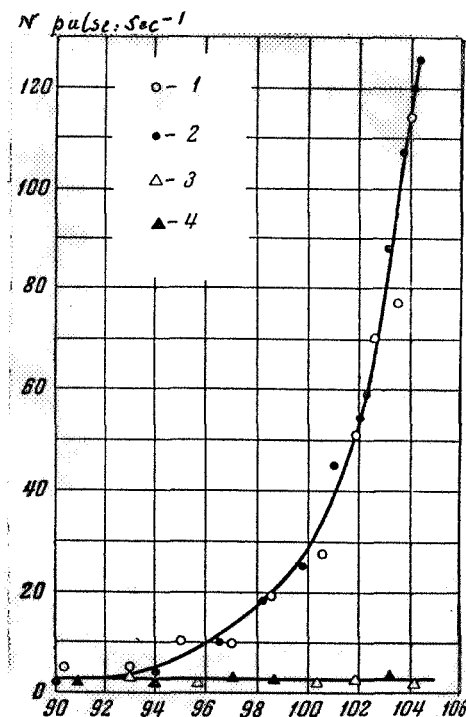


Fig. 6

21 July evening launching  
Measurements at ascent and desc.  
1, 2, basic counter.  
3, 4 — check counter.

(Fe XIV  $\lambda 5303$  and Fe X  $\lambda 6374$ ), which according to measurements by Friedman, correlate with the intensity of X-ray radiation, were computed by us according to data of Kislovodsk and Alma-Ata coronal stations and was found to be 3.4 at the day of launchings. Seven chromospheric flares were registered during the day. No flares took place at time of first launching, while the moment of the second launching corresponded to the extinction stage of a class I flare.

The zenithal angle of the Sun at the moment of the morning launching was near  $91.5^\circ$ , and at the time of the evening launching near  $90.5^\circ$ .

Trajectory measurements were not carried out during the first launching. The height of container's lift was obtained by way of computations. During the second launching, it was obtained according to direct measurements.

The dependence on the altitude of the counting rates of the operating and check counters for the morning launching is presented in Fig. 5. Computed altitude values were used here. The control (check) counter readings, devoid of magnetic shield, coincide with those of the operating counter within the limits of the precision of measurements.

The dependence on altitude of the counting rates of both counters for the evening launching is presented in Fig. 6. The check counter readings, turned at  $15^\circ$  from the direction to the Sun, correspond to cosmic background level.

These data attest about the absence of interferences from corpuscular streams, just as does the character of counting rate increase with altitude. Consequently, the readings of the operating counters may be considered as due to the Sun's X-ray radiation. A notable X-ray flux was registered beginning with the 95 km altitude.

The maximum measured counting rate lies within the limits of counters' calibration characteristic, and that is why no correction for the "dead time" was entered. Owing to the stable orientation of the container in respect to the Sun, there was no need to enter the correction for the angular dependence of counters' efficiency.

One may obtain from these data the energy distribution and the magnitude of energy flux in the registered portion of the Sun's spectrum beyond the limits of the atmosphere. The working out of data was carried out in the following manner: The mass of the inclined column of air, of  $1 \text{ cm}^2$  cross section, lying between the device and the Sun, was computed for various points of rocket's trajectory. This was achieved with the aid of the expression  $m_{\text{incl}} = m_{\text{vert}} \cdot \Phi(z)$ , where  $m_{\text{vert}}$  is the mass of the vertical column of air numerically equal to air pressure at the given altitude, and the factor  $\Phi(z)$  is determined by the zenithal angle of the Sun —  $z$ . The atmosphere parameters, brought out in the work by Mikhnevich and Khvostikov [17], were utilized in the computation of  $m_{\text{vert}}$ ; they are very near the magnitude of parameters of the atmosphere model examined in the Champion and Mintzner paper [18]. The factor  $\Phi(z)$  for angles  $z$  from  $0$  to  $90^\circ$  is computed by Bemporad [19] in the assumption that the rays do not undergo refraction. The magnitude  $\Phi(z)$  for greater angles  $z$  (more than  $90^\circ$ ), which are precisely such as the angles of our experiments, was computed by reduction to the case  $z \leq 90^\circ$  with the help of the expression

$$m_{\text{AS}} = p_A \Phi(z + \alpha) = m_{\text{BS}} + (m_{\text{BS}} - m_{\text{AS}}),$$

where  $m$  is the mass of the air at the corresponding portion of the ray's path;  $p_A$  is the pressure at the point A. This correlation follows directly from the examination of Figure 7 (next page).

In that drawing  $S$  is the Sun,  $A$  is the point at which the device is situated,  $B$  is an auxiliary point, at which the zenithal angle is  $90^\circ$ . The mass in the section  $BA$  is computed as the difference of masses at portions  $S'B$  and  $S'A$ .

Introducing the factor  $\Phi(z)$ , we find

$$m_{AS} = p_B \Phi(90^\circ) + p_B \Phi(90^\circ) - p_A \Phi(90^\circ - \alpha) .$$

The results of computations  $m_{incl} = m_{AS}$  for both launchings are brought forth in Fig. 8. The magnitude of the factor  $\Phi(z)$  resulted quite great (respectively  $\Phi(z) = 80$ , and  $\Phi(z) = 45$  for the morning and the evening launchings, which is due to a very low position of the Sun near the horizon.

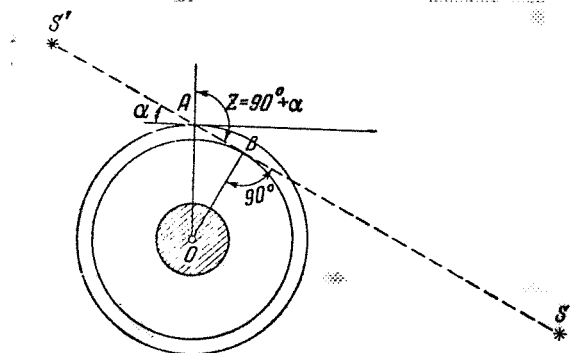


Fig. 7. Construction for the determination of the factor  $\Phi(z)$  for  $z > 90^\circ$ .

Plotted is in Fig. 9 the counting rate at the counters as a function of  $m_{incl}$  for both launchings, recalculated according to graphs of Fig. 5 and 6. On the basis of the curves of Fig. 9, of mass coefficients of air absorption for a monochromatic emission of various wavelengths (Fig. 10) [15] and of the curve of counters' spectral sensitivity (Fig. 2), it is possible to construct the distribution of the number of photons in the studied portion of the Sun's spectrum, in the assumption that this portion is continuous.

With this in mind, the surface under the distribution curve is approximated by the sum

$$\sum_{i=1}^n N_{\lambda_i} \Delta \lambda_i,$$

where  $N_{\lambda_i}$  is the number of photons in the interval  $\lambda_i$  and  $\lambda_i + \Delta \lambda_i$ ;  $\Delta \lambda_i$  is chosen such, that the absorption coefficient within the limits of that interval be sufficiently constant. On the curve of Fig. 9,  $n$  points are chosen, and for the determination of  $N_{\lambda_i}$  a system of the following  $n$  equations is used:

$$\sum_i \eta_{\lambda_i} \beta_{1, \lambda_i} N_{\lambda_i} \Delta \lambda_i = N_1,$$

$$\sum_i \eta_{\lambda_i} \beta_{2, \lambda_i} N_{\lambda_i} \Delta \lambda_i = N_2,$$

$$\dots \dots \dots$$

$$\sum_i \eta_{\lambda_i} \beta_{n, \lambda_i} N_{\lambda_i} \Delta \lambda_i = N_n,$$

solved approximately. Here  $\eta_{\lambda_i}$  is the counter's efficiency for the wavelength  $\lambda_i$ ;  $\beta_{k, \lambda_i}$  is the transmission factor of the mass  $m_k$  corresponding to the point  $k$  on the curve of Fig. 9 for a wavelength  $\lambda_i$ ;  $N_k$  is the counting rate corresponding to the point  $k$  on the curve in Fig. 9.

The so obtained distribution curves of the number of photons as a function of the wavelength for both launchings, computed in a  $1 \text{ cm}^2$  surface, and for a spectral interval of  $1 \text{ \AA}$ , are plotted in Fig. 11. The computations for the wavelength portions  $8 - 11 \text{ \AA}$ , and shorter than  $3 \text{ \AA}$ , are very inaccurate, as the contribution of these spectrum portions to the registered radiation flux is relatively small (the radiation is very strongly absorbed in the  $8 - 11 \text{ \AA}$  spectral region even near the summit of the trajectory, while in the region below (shorter)  $3 \text{ \AA}$ , its intensity is very small). That is why the corresponding portions of the curves of Fig. 11 are indicated by dotted lines.

It is easy to pass from curves of Fig. 11 to energy distribution along the spectrum. The energy contained in the region shorter than  $8 \text{ \AA}$ , constitutes beyond the limits of the atmosphere

$3.6 \cdot 10^{-4}$  ergs  $\cdot$  cm $^{-2}$   $\cdot$  sec $^{-1}$  for the morning launching, and  $1.6 \cdot 10^{-4}$  ergs  $\cdot$  cm $^{-2}$   $\cdot$  sec $^{-1}$  for the evening launching. The energy contained in the spectrum region shorter than 10 A constitutes respectively  $7.3 \cdot 10^{-4}$  and  $3.2 \cdot 10^{-4}$  ergs  $\cdot$  cm $^{-2}$   $\cdot$  sec $^{-1}$ . Taking into account

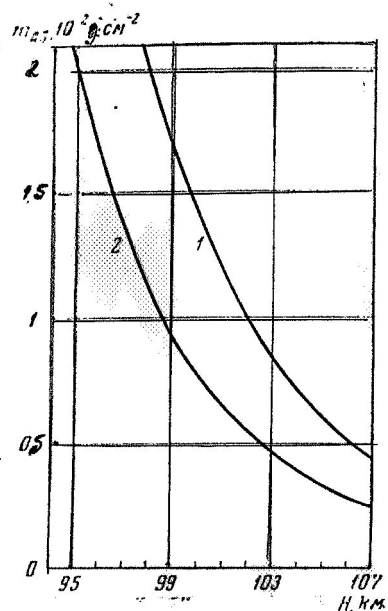


Fig. 8. Mass  $m_{AS}$  of the inclined absorbing air column, as a function of container's height:

1 — morning launching  
2 — evening " "

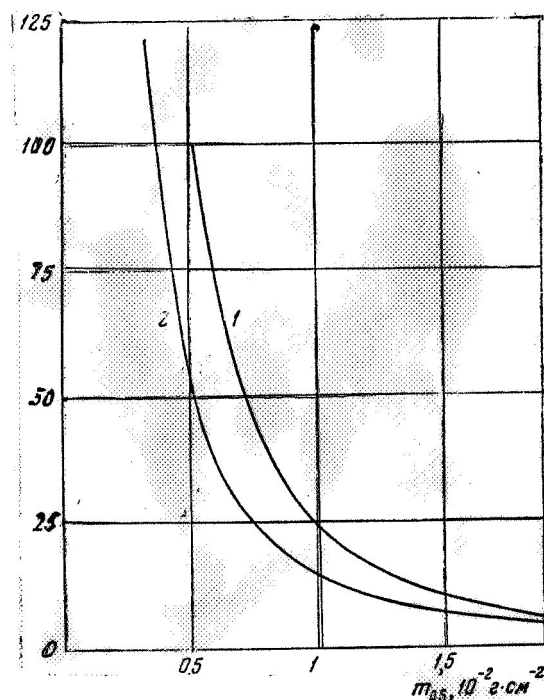


Fig. 9. Counting rate  $N$  as a function  $m_{AS}$ :

1 — morning launching,  
2 — evening " "

the possibility of a two or threefold uncertainty in the magnitude of counters' absolute efficiency in both launchings, it is difficult to state whether or not this difference in energies is real. As to the rather small difference in the course of the curves for energy distribution in both launchings, it is likely conditioned by a certain difference in counters' spectral sensitivity, and by the inaccuracy of air mass determination. The shape of both curves may be practically considered as same.

It is natural to consider in the first approximation the free-free transitions — electron brehmmastrahlung in the field of hydrogen and helium ions as the basic source of continuous radiation (emission) in the examined part of the spectrum. Bound-free transitions in hydrogen and free-free transitions in the field of other ions included in the corona only insignificantly increase the radiation flux at temperatures exceeding  $10^6$  °K, as computations by Kogan [20] and Elwert [7] have shown.

Fig. 11 indicates by dots the distribution of the number of photons in the spectral region of interest to us, computed by means of brehmstrahlung formula [7]:

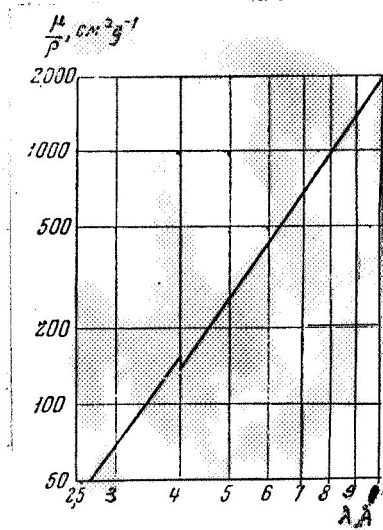


Fig. 10. Dependence of the mass absorption coeffic.  $\mu/p$  of the air on the wavelength of the monochromatic emission.

$$N_\lambda = \text{const } N_e N_i T_e^{-\frac{1}{2}} g \frac{d\lambda}{\lambda} \exp \left\{ -\frac{hc}{k\lambda T_e} \right\}.$$

The computation was made for  $T_e = 4.5 \cdot 10^6$  °K and the Gaunt factor  $g \sim 1$  [6]. The theoretical curve was normalized in such a way, that it coincides with the curve 1 in Fig. 11. for a wavelength  $7 \text{ \AA}$ . As follows from Fig. 11, the theoretical curve reproduces very well the observed energy distribution in the spectrum.

The introduced value of electron temperature exceeds substantially however, the value  $T_e \sim 1 + 3 \cdot 10^6$  °K, obtained in our subsequent experiments with spaceships. This temperature increase can not be ascribed to the flare, since there were no flares during morning launching. The increased temperature value may possibly be explained by the presence of highly active regions in the Sun on the day of launchings. It must also be noted that the

experiment was conducted in a period close to the solar activity maximum. Friedman takes advantage of radiation's color temperature and admits its being near  $2 \cdot 10^6$  °K. The curve of Fig. 11 corresponds to a color temperature of about  $3 \cdot 10^6$  °K, which is exceeding that measured by Friedman.

Friedman's measurements are related to solar activity minimum in 1953, while our measurements with the help of the spacecraft took place in December 1960, thus corresponding to the period after the maximum phase passing. The comparatively high absolute value of radiation flux, registered on 21 July 1959, [also speaks in favor of a sharp dependence of radiation's temperature and intensity upon the solar cycle phase.]

On the other hand, the fact that measurements were carried out at time of very low position of the Sun near the horizon, constitutes a peculiarity of the described experiments, clearly distinguishing them from Friedman experiments. The radiation path in the atmosphere was very great, and comparatively small inaccuracies of the atmosphere model admitted by us for the computations, may lead to serious variations in the computed values  $m_{incl.}$ , and consequently, also in the spectral distribution and absolute value of energy flux. Further systematic measurements of energy distribution near the short-wave edge of the solar emission

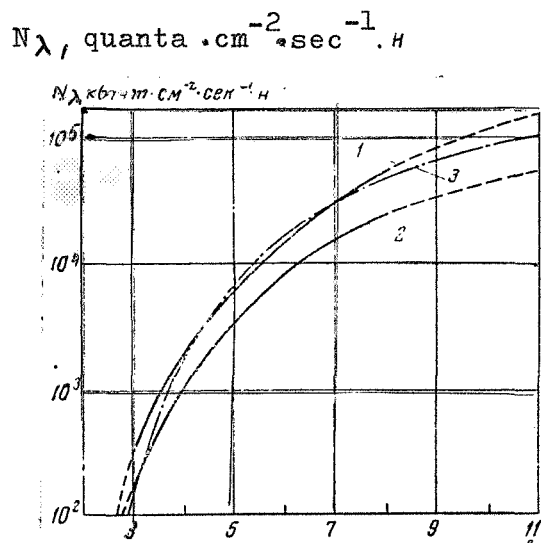


Fig. 11. Distribution in the Sun's spectrum of the number of photons: 1 — morning launch. 2 — evening launching. 3 — theoretical curve, computed by \*)

\*) brehmstrahlung with  $T_e = 4.5 \cdot 10^6$  °K.

spectrum thus appear to be indispensable.

In the subsequent two papers, we shall present the results of measurements carried out by means of the 2nd and 3rd spaceships-satellites, together with the description of the electronic equipment utilized.

\*\*\* THE END \*\*\*

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NASA HEADQUARTERS, Washington D. C.  
25 February 1962.

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